PROSPECTS FOR TRULY INTEGRATED BUILDING PERFORMANCE SIMULATION

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ABSTRACT

To facilitate multi-variate performance appraisal all aspects of a building must be treated simultaneously. This paper describes how the disparate technical domains defining a building's thermodynamic state are coupled within the ESP-r integrated simulation package. Essentially, the equation-sets defining each domain are processed by customised solvers, while the domain interactions are handled by ensuring that the equation-sets for a given domain are established as a function of information defining the evolution of any coupled domains.

Keywords: Building performance simulation, integrated modelling, domain coupling.

INTRODUCTION

It is widely accepted that explicit performance appraisal by simulation defines a best practice approach to building design. In the UK — after a decade of promotion by BEPAC (1999) and the regionally based Energy Design Advice Scheme (McElroy et al 1997) — practitioners are well aware of the potential of simulation. Building on this foundation, a recent initiative aims to embed simulation within energy sector businesses (McElroy and Clarke 1999). This is being achieved through 'Supported Technology Deployments' by which companies are able to obtain in-house support from modelling specialists seconded to the design team.

It may be expected that as the rate of uptake of simulation accelerates, user expectations will grow, especially in relation to integrated modelling by which a building's multi-variate state may be appraised. Satisfying these expectations will require the non-trivial integration of several, non-trivial technical domains. This paper describes a possible approach to domain conflation as encapsulated within the ESP-r system.

THE CONFLATION APPROACH

The principle of superimposition has long been used by modellers to determine the response of a system to some excitation by summating the responses, determined independently, of the system's component parts. If these parts are strongly interacting, as in buildings, then this will lead to an inherent inaccuracy because the parts are decoupled. The practice of assuming model parameters (e.g. surface heat transfer coefficients, fabric conductivity, etc.) to be time invariant has the effect of decoupling parts and thereby rendering the principle of superimposition acceptable.

The aim of an integrated approach is to preserve the integrity of the entire building system by simultaneously processing all energy transport paths to a level of detail commensurate with the objectives of the problem to hand and the uncertainties inherent in the describing data. To this end, a building should be regarded as being systemic (many parts make the whole), dynamic (the parts evolve at different rates), non-linear (the parameters depend on the thermodynamic state) and, above all, complex (there are myriad intra- and inter-part interactions). To achieve high modelling integrity, a simulation program must preserve these intrinsic characteristics.

Within the ESP-r system (Clarke 1985) this integrity issue is addressed by ensuring that the mathematical models for conduction, air movement, radiation exchange and so on are processed simultaneously within a simulation. Because the whole system matrix equation is large and sparse, and the domain equations have disparate characteristics — linear, non-linear, orders of magnitude variation in the related time constant, weakly and strongly interacting, etc. — a partitioning technique is employed. In the approach, customised (and optimised) solvers are applied to each domain equation-set, with interdomain message passing used to ensure that the parameters and source terms of the governing equations are established (at each time-step) as a function of information linking coupled domains. Precedence protocols are used to dictate the order of invocation of domain solution. For example, the air flow domain is solved prior to the building thermal domain because the latter has a larger time constant and therefore the state variables will change more slowly. Iteration is used to handle the case of strongly interacting domains.

Figure 1 summarises the coupled domains represented within ESP-r at the present time. To elaborate the process of domain conflation, the following couplings are described here:

- □ building thermal processes and natural illuminance distribution;
- □ building and plant thermal processes and distributed fluid flow;
- □ building thermal processes and intra-room air movement;
- □ building distributed air flow and intra-room air movement;
- □ construction heat and moisture flow.

At the theoretical level, ESP-r employs a finite volume approach to the conservation of energy, mass, electrical power, etc. Essentially, the building and its HVAC system is discretised and equations of the following form established for each fluid region to represent the conservation of energy, mass and momentum (Clarke 1985, Negrão 1995).

$$\frac{\partial}{\partial t}(\rho\phi) = \frac{\partial}{\partial x_i}(J_\phi)_i + S_\phi \tag{1}$$

where ϕ represents any transport variable (velocity components, temperature, etc.) and $(J_\phi)_i$ is the convective and diffusive fluxes defined as

$$\Gamma_\phi \frac{\partial \phi}{\partial x_i} - \rho V_i \phi .$$

The transport variables, diffusion coefficient, Γ_ϕ, and the source term, S_ϕ, are given in Table 1 for each conservation equation type. The integrated form of equation (1) over a finite volume P assumes the following form

$$\frac{\partial}{\partial t}(\rho\phi V)_P = (J_\phi A)_{CS} + S_\phi V \tag{2}$$

where V is volume, A is the flux path area, CS designates the control surface area and J_ϕ represents the convective and diffusive fluxes which are usually approximated as a function of the transport property differences evaluated at the center of P and its neighbours.

The conservation of energy within the building fabric and HVAC system components can be similarly treated:

$$\frac{\partial}{\partial t}(\rho\phi V)_I = (J_\phi A)_{CS} + S'_\phi \tag{3}$$

where ϕ is now temperature, moisture content, etc. and S'_ϕ is a source of energy or mass generation. J_ϕ is the flux of the transport property at the surface, usually approximated as an interaction between I and other regions, j, via conductive, convective and radiative flow-paths:

$$(J_\phi A)_{CS} = \sum_{j=1}^{N}(K_{j,I}(\phi_J - \phi_I)) \tag{4}$$

where $K_{J,I}$ is a linearised flow conductance between regions j and I, and t is time.

Within ESP-r, equations (2) and (3) are the basis of conservation equations established for each finite volume comprising the system. At each simulation time-step, equations of a given type are processed by a customised solver, with inter-solver message passing to handle the domain interactions as described in the following sections.

THERMAL/ VISUAL DOMAINS

Here the coupling point is the source term of equation (3). ESP-r allows the placement of multiple light sensors in a thermal zone in order to provide a basis for individual area lighting control, or average plane illumination for overall zone control. Luminaires, individually, or in groups, can then be subjected to control action based on the sensed illuminance.

This coupling links the indoor illuminance distribution to the heat gain from luminaires via a controller comprising a photocell and dimming device. The modulated heat gain is then injected as a source term to the appropriate finite volume equations representing the heat balance of the room air and surfaces. The coupling is achieved via a simulation-time link (Hand et al 1998, Janak 1998) between ESP-r and Radiance (Ward-Larson and Shakespeare 1998) as summarised in Figure 2.

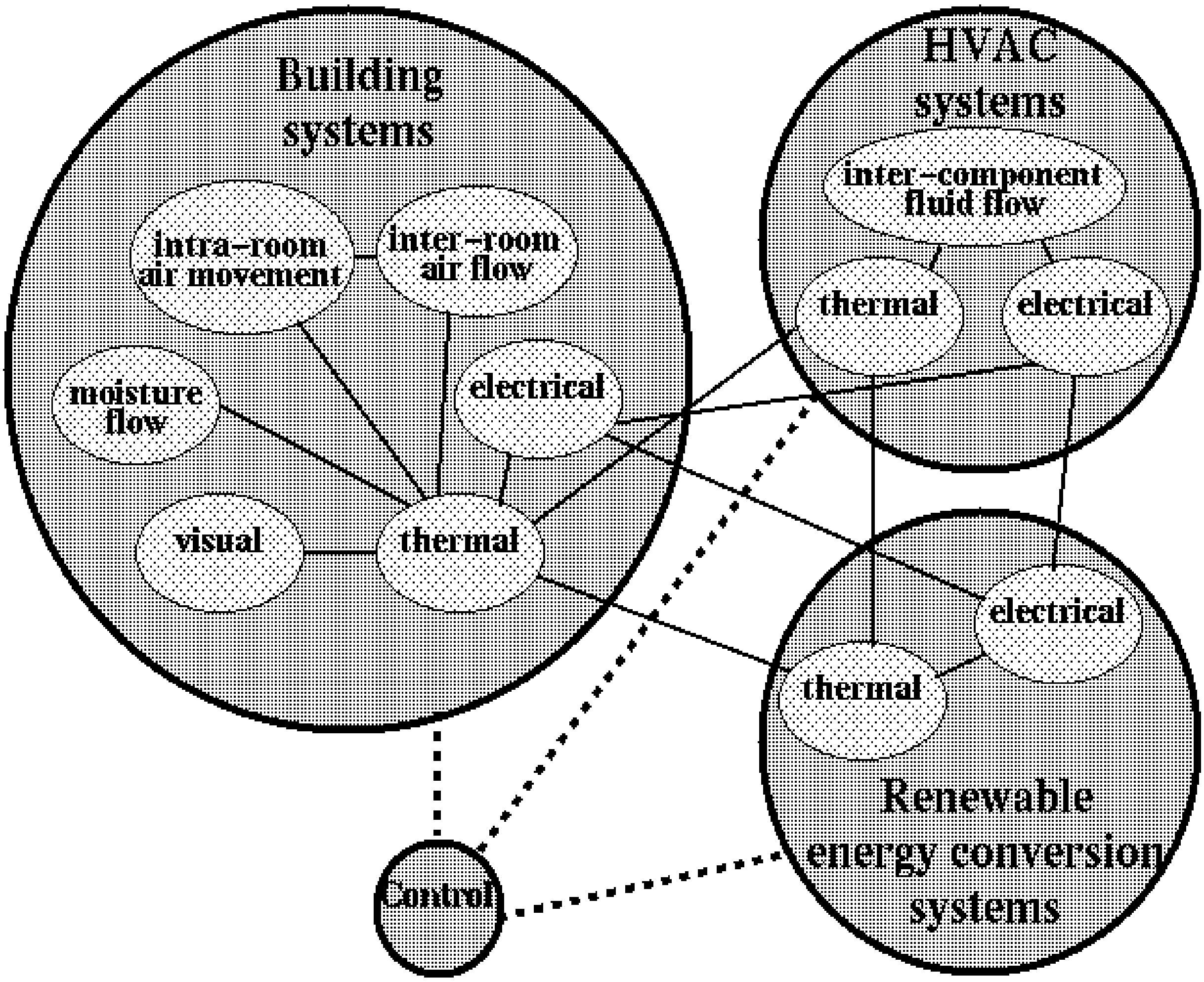

Figure 1: Domain coupling within the ESP-r system.

At each simulation time-step, ESP-r's luminaire control algorithm initiates the daylight simulation. Radiance is then controlled by ESP-r to carry out several tasks as follows:

□ transfer to Radiance of data defining the current sun position, solar irradiance and building model state (e.g. window blind position);

□ generation of the sky luminance distribution (Perez et al 1993) and re-building of the Radiance scene model;

□ calculation of the internal illuminance for the defined sensor locations and transfer of these data to the luminaire controller;

□ determination of the luminaire's status and hence the casual gain associated with lights at the current time-step.

ESP-r supports shading device and luminaire control on the basis of tests applied to active model parameters. For example, shading devices may be activated on the basis of room or ambient temperatures, or facade irradiance, while luminaire control is implemented as a function of photocell position, vision angle, controller set-point, switch-off lux level, switch-off delay time and minimum stop. Two dimming control algorithms are available. An *integral reset controller* adjusts the dimming level so that the measured photocell signal is kept at the measured signal from the artificial lights as determined by night-time photocell calibration. A *closed loop proportional controller* adjusts the dimming level in proportion to the difference between the photocell signal and the night-time reference level. With this controller, a day-time calibration must be performed to determine the linear control function slope. (As an aside, information on luminaire status may also be used to set the source term of an electrical power flow conservation equation to modulate the boundary condition load within an active electrical network model (Kelly 1998).)

THERMAL/ DISTRIBUTED FLUID FLOW DOMAINS

Here the coupling point is the coefficients of the $K_{j,I}$ term of equation (4). Within ESP-r, the coupling between heat and fluid flow is achieved by iteratively solving the building/HVAC thermal model and a fluid flow network (Clarke and Hensen 1990). The flow network is composed of nodes (representing rooms and locations within the HVAC system), components (representing the leakage paths and pressure drops associated with doors, windows, supply grills, ducts, fans, etc.) and connections joining nodes by components (Figure 3). A mass balance is performed at each time step to solve the flow through each connection. These flows are then used to establish the mass flow dependent coefficients of the building and plant thermal equations for the next time step, with iteration invoked for the case of strongly coupled flows.

The numerical processing scheme implemented within ESP-r is as follows.

- □ The energy conservation equations corresponding to the finite volumes which represent the HVAC components and air/water distribution network are established on the basis of the latest values of the building-side state variables and HVAC mass flows.

- □ The HVAC energy balance matrix equation is then solved by a customised numerical method which includes any defined control action (Aasem 1993).

- □ The energy conservation equations corresponding to the finite volumes which represent the building constructions, surfaces and air volumes are then established on the basis of the latest values of the HVAC flux inputs and building air flows.

- □ The building energy balance matrix equation is then solved by a customised numerical method which encapsulates the effect of the different possible building-side control actions (Clarke 1985).

- □ The whole-system (building and HVAC) fluid flow equation-set is now established on the basis of the newly computed building and HVAC state variables and solved by a Newton-Raphson technique applied iteratively to minimise the flow residuals at all non-boundary network nodes (Clarke and Hensen 1990).

- □ Finally, the predicted network mass flows are delivered for use in the estimation of the coefficients of the building and HVAC conservation equations at the next time-step and the above process repeats. A time-step controller may be activated to prevent the evolution of the simulation clock in cases where the newly computed building, HVAC or flow network state-variables differ markedly from the latest values assumed when their corresponding matrix equations were established.

Since the time constant associated with the equations representing the HVAC system may be an order of magnitude smaller than those representing the building, a facility is provided to allow the former equations to be established and solved at a greater frequency than the latter. The HVAC and fluid flow solution frequencies are always matched.

INTER-/ INTRA-ROOM AIR FLOW DOMAINS

The above approach to building air flow modelling has significant limitations: because momentum effects are neglected, intra-room air flow and temperature distribution cannot be determined; and because of the low resolution, local surface heat transfer is poorly represented. In an attempt to address these limitations, the resolution of ESP-r's air flow modelling was enhanced by the integration of a CFD capability (Negrão 1995). Now the focus of coupling is the interface between the CFD and building thermal domains, and between the CFD and network flow domains.

In relation to a three-dimensional, staggered, orthogonal grid, the $k-\varepsilon$ model is used to estimate the turbulent diffusion of momentum and heat while log-law wall functions are used to account for the viscous effects in the near-wall regions. Buoyancy forces are included in the momentum equations using the Boussinesq approximation. The building thermal and CFD domain solvers then co-operate as follows.

- □ Because it is recognised that the above models have limited applicability when applied to non-steady, low Reynolds Number flows as encountered in buildings, a conflation controller (Beausoleil-Morrison 1999) is invoked to assess applicability at each time-step. This controller examines the zone's flow behaviour and, where possible, assigns empirical surface convective heat transfer correlations. A CFD domain is then established and the current building state used to define the boundary condition.

- For surfaces assigned a convection correlation, the corresponding wall functions are replaced by a directly calculated heat flux. Otherwise, the convective heat flux is determined from the CFD-derived flow and temperature fields based on the active wall functions and the surface averaged heat transfer coefficients are passed to the building surface energy balance equation.

- Where an air flow network and CFD domain are both active, the network node representing the room is removed and new network connections are added to effect a coupling with the CFD domain (Clarke et al 1995) as shown in Figure 4. The CFD-derived air flows into and out of the room are then treated as sources or sinks of mass within the flow network solution.

Several enhancements to ESP-r's air movement modelling capabilities are underway. These include the implementation of an improved turbulence model (Beausoleil-Morrison and Clarke 1998), the ability to handle intra-room obstructions, and the computation of the local mean age of air (Stankov and Denev 1999).

CONDUCTION/ MOISTURE FLOW DOMAINS

ESP-r applies mass and energy conservation considerations to a stationary, homogeneous, isotropic, constructional control volume to conflate heat and moisture flow within multi-layered constructions (Nakhi 1995).

For the moisture term:

$$\rho_o \zeta \frac{\partial (P/P_s)}{\partial t} + \frac{d\rho_l}{dt} = \frac{\partial}{\partial x}\left(\delta_P^T \frac{\partial P}{\partial x} + D_T^P \frac{\partial T}{\partial x}\right) + s \quad (5)$$

where ρ is density (o and l denote porous media and liquid respectively), ζ is the moisture storage capacity, P is the partial water vapour pressure, P_s is the saturated vapour pressure, δ is the water vapour permeability, D is the thermal diffusion coefficient and s is a moisture source term. T and P denote temperature and pressure driving potentials respectively, with the principal potential given as the subscript.

For the energy term (in one dimension):

$$[\rho_o(c_o + c_v u_v) + c_l \rho_l] \frac{\partial T}{\partial t} + h_v \frac{\partial \rho_v}{\partial t} + h_l \frac{\partial \rho_l}{\partial t} \quad (6)$$
$$= \frac{\partial}{\partial x}\left(\lambda \frac{\partial T}{\partial x}\right) - \frac{\partial h_s J_v}{\partial x} + g$$

where c is specific heat, u is moisture content, T is temperature, λ is heat conductivity, J_v is the vapour mass flux, g is a source of heat and h_v, h_l and h_s are the enthalpies of vapour, liquid and moisture flux source respectively.

For the condensation and evaporation processes, a control equation is implemented as a one-way liquid value connected to the control volume. When the relative humidity reaches its maximum value, the valve opens to deliver the condensation to an imaginary tank. Conversely, when the relative humidity falls below its maximum value, liquid is returned to the control volume where it re-evaporates. At the present time, this process is implemented as a function of the saturation pressure only: future modification of the algorithm is planned for the case of capillary condensation.

Use of the above equations, after transformation to a finite difference form, allows for the solution of the three dependent variables, P, T and ρ_l, for each control volume within a multi-layered construction when evolving through time under the influence of the boundary heat and mass transfers. The solution proceeds as follows.

- Because the energy equations can often be linearised, while the moisture equations typically cannot, the two equation systems are processed separately but under global iteration control to handle the coupling effects. This allows each equation-set to be integrated at different frequencies depending on the characteristics of the system they represent.

- For the energy equations, a matrix partitioning technique is employed as reported elsewhere (Clarke 1985). The method allows variable time-stepping and incorporates iteration for non-linear cases, i.e. where the equation coefficients are a function of the state variables.

- Because of their highly non-linear nature, the moisture flow equations are solved by a Gauss-Seidel method, with linear under-relaxation used to prevent convergence instabilities in the case of strong non-linearity or where discontinuities occur in the moisture transfer rate at the maximum relative humidity due to condensation. A false time step relaxation factor is used. This acts to magnify the vapour storage term at the future time-row and so lessen the difference between the present and future values of the dependent variable. Because some of the terms within the moisture equations are dependent on temperature, the moisture solution is constrained to proceed at a frequency matched to or less than that imposed on the energy equations.

- The global iteration control is invoked whenever the liquid mass variations exceed some specified limit. When this occurs, the energy matrix is resolved on the basis of the recently computed moisture-side variables but with no recalculation of the energy-side parameters.

- For highly coupled cases, both equation systems are solved at matched and small time-steps.

Based on the foregoing theory, with temperature and partial vapour pressure used as the transport potentials for moisture, a one dimensional, coupled heat and moisture transport model has been implemented within ESP-r (Nakhi 1995).

CONCLUSIONS

This paper has described the approach to domain coupling as implemented within the ESP-r system. The contention is that users will expect future tools to explicitly encapsulate real world phenomena and that this, in turn, will require truly integrated building performance prediction tools. This paper has presented a approach to theoretical domain conflation, as implemented within the ESP-r system. This approach permits independent domain equation-set processing rather than constraining each equation-set to a single solution procedure. Domain interaction is then achieved by linking the outcome from one domain to the coefficients and source terms of the equations representing a coupled domain.

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Equation Type	ϕ	Γ_ϕ	S_ϕ
Continuity	1	-	-
Momentum	V_i	μ_{ef}	$-\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_i}\left[\mu_{ef}\left(\frac{\partial V_j}{\partial x_i}\right)+\left(\frac{\partial V_i}{\partial x_j}\right)\right]-\rho g_i$
Energy	T	Γ_T	$\frac{q'''}{c_p}$
Species	C	Γ_C	$\dot{m}'''$
Turbulence Energy	k	$\frac{\mu_{ef}}{\sigma_k}$	$G - C_D\rho\varepsilon - G_b$
Energy dissipation	ε	$\frac{\mu_{ef}}{\sigma_\varepsilon}$	$C_1\frac{\varepsilon}{k}G - C_2\rho\frac{\varepsilon^2}{k} - C_3\frac{\varepsilon}{k}G_b$
$\Gamma_T = \frac{\mu}{Pr}+\frac{\mu_t}{\sigma_T}$; $\Gamma_C = \frac{\mu}{Sc}+\frac{\mu_t}{\sigma_C}$; $\mu_{ef} = \mu_t + \mu$; $\rho = \rho(T, C)$			
$G_b = g\left(\beta_T\frac{\mu_t}{\sigma_T}\frac{\partial T}{\partial x_i}+\beta_C\frac{\mu_t}{\sigma_C}\frac{\partial C}{\partial x_i}\right)$; $G = \mu_t\left(\frac{\partial V_i}{\partial x_j}+\frac{\partial V_j}{\partial x_i}\right)\frac{\partial V_i}{\partial x_j}$			
$C_D = 1.0$; $C_1 = 1.44$; $C_2 = 1.92$; $\sigma_k = 1.0$; $\sigma_\varepsilon = 1.3$; $\sigma_T = 0.9$; $\sigma_C = 0.9$			

Table 1: CFD transport variables, diffusion coefficients and source terms

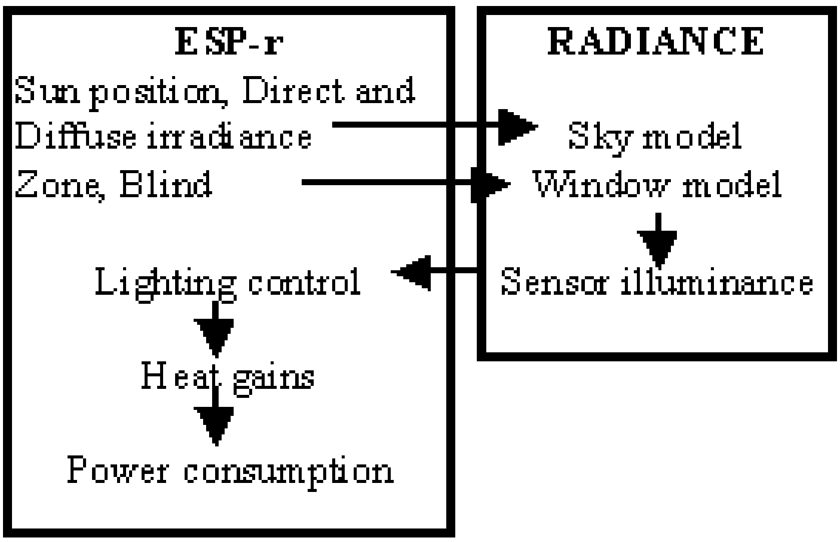

Figure 2: ESP-r/ Radiance link.

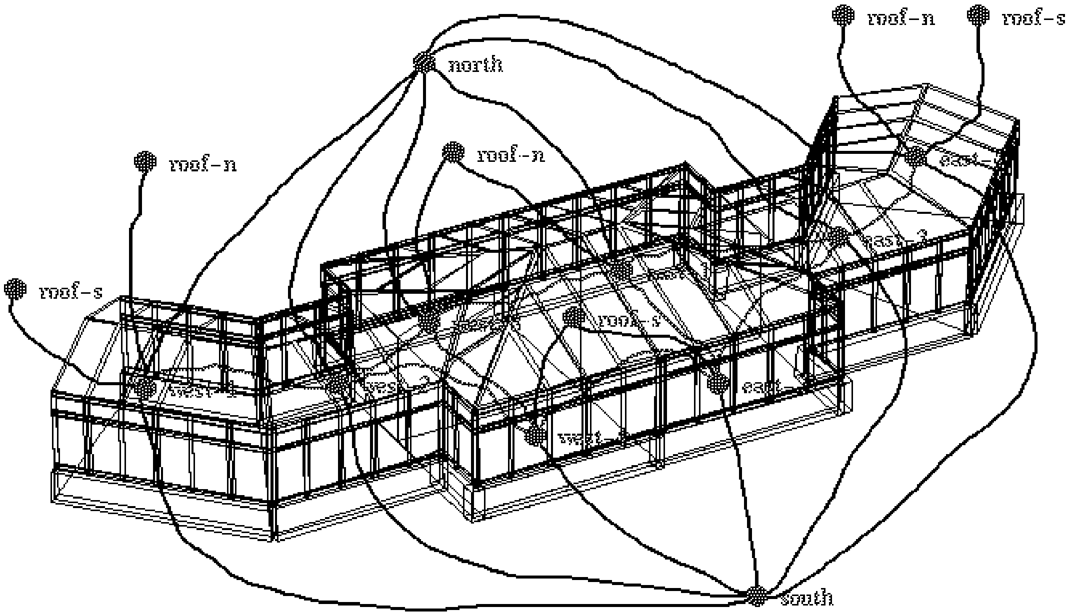

Figure 3: Thermal/ fluid flow link.

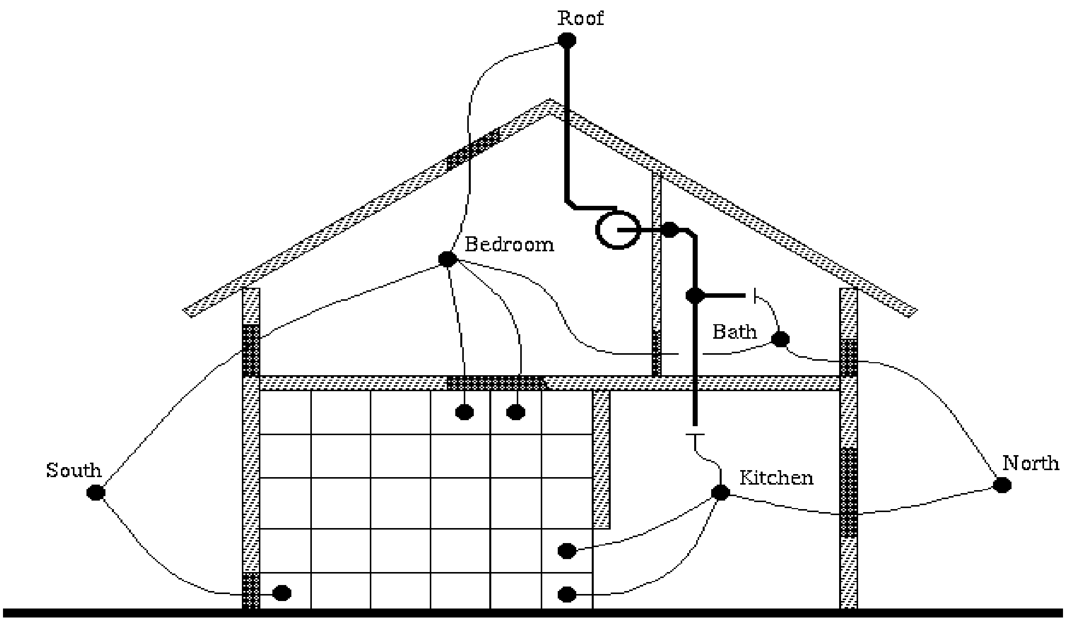

Figure 4: CFD/ network air flow link.